SHAKING TABLE TESTING OF A MULTI-STOREY POST-TENSIONED TIMBER BUILDING

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ABSTRACT

This paper describes the preliminary results of shaking table testing of a post-tensioned timber framed building performed in the structural laboratory of the University of Basilicata in Potenza, Italy. This experimental campaign is part of a series of experimental tests in collaboration with the University of Canterbury in Christchurch, New Zealand. The specimen is a 3-dimensional, 3-storey, 2/3rd scaled and is made up of post-tensioned timber frames in both directions. During the testing programme the specimen will be tested both with and without the addition of dissipative steel angles which are designed to yield at a certain level of drift. These steel angles release energy through hysteresis during movement thus increasing damping. This paper discusses the testing set-up, modelling methods and preliminary experimental dynamic results. During the preliminary stage of testing, the specimen has been subjected to hammer impact excitations, sine-sweep ground motion and one natural earthquake record with a low level of seismic loading. The seismic response has been compared with numerical predictions using the finite element program SAP2000 in terms of periods of vibration and a time-history response.

Keywords: Pres-Lam, dynamic testing, multi-storey post-tensioned timber frame, energy dissipation systems, non-linear numerical modelling.

1. INTRODUCTION

The use of post-tensioning technology to connect structural timber elements enables the design of multi-storey buildings having large bay lengths (8-12m), reduced structural sections and lower foundation loads with respect to traditional timber construction methods. The design of this type of structure is based on the rocking motion which occurs at the interface of the beam and column members during seismic loading. Rocking creates a concentrated nonlinear displacement which must be accounted for in design and should not create damage to secondary members, flooring or non-structural elements. The key to this type of connection is given by the ratio β between the

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moment resistance provided by the post-tensioning and the total moment resistance provided by the connection (Fig. 1).

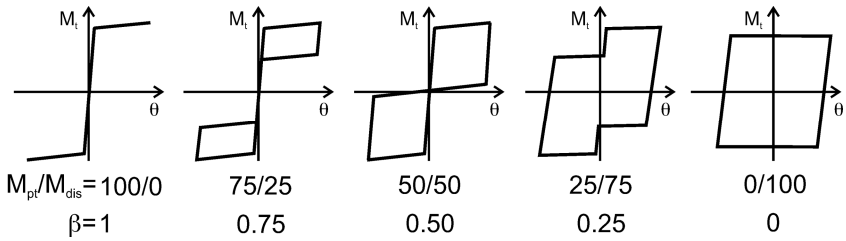


Figure 1: Moment response with varying levels of the parameter β

Although a simple concept, this ratio provides the cornerstone in the understanding of system performance. Clearly, during design this choice affects both the damping and moment capacity of the system and therefore changing this value will have a direct effect on both capacity and demand.

The post-tensioned timber concept (under the name Pres-Lam) has been developed at the University of Canterbury (UoC), in Christchurch, New Zealand, and has been extensively tested (beam-column, wall/column-foundation, 3d frame and wall structure) in the structural laboratory of UoC. This testing has however solely used Laminated Veneer Lumber (LVL) a product widely available in New Zealand but not globally.

An extensive dynamic experimental testing programme is scheduled to be performed in the structural laboratory of the University of Basilicata (UNIBAS) in Potenza, Italy. This work is part of a collaborative experimental campaign between UNIBAS and UoC. The complete study will evaluate the feasibility of applying jointed ductile post-tensioning technology, originally conceived for use in concrete structures (Priestley et al. 1999), to glue laminated timber (glulam). The aim of the project is to further study the seismic performance of the system and improve understanding of its dynamic performance.

In stage one of this current collaborative project a full-scale beam-column joint was designed, fabricated, constructed and tested in the structural laboratory of UNIBAS. This beam-column joint was the first to use glue laminated timber (glulam) in post-tensioned timber construction. The experimental programme was completed midway through 2011 providing excellent results and began to answer key questions regarding system performance. Modelling and design procedures were also implemented and verified (Smith et al. 2012).

In stage two of this project a 3-dimensional, 3-storey timber structure made up of frames in both directions composed of post-tensioned timber will be dynamically tested at UNIBAS laboratory considering different natural earthquake inputs. During the experimental campaign the size of the structural members, building layout and mass will not be altered, however different values of post-tensioning and steel moment capacity contributions (thus variations in the value β) will be investigated. This paper will first describe the detailing and testing set-up of the experimental model

and then compare preliminary experimental results with blind predictions provided by the numerical SAP models.

2. THE EXPERIMENTAL CAMPAIGN

The prototype structure constructed in the structural laboratory of UNIBAS (Fig. 2) is three stories and has single bays in both directions (Fig.2). All design has been performed in accordance with the current version of the Italian and European design codes (NTC 2008; EC5 2005). The test frame is made from glulam grade GL32h and the building has been designed to represent an office structure (live loading Q=3kPa for level I and II) and has a roof garden (Q=2kPa). A scale factor of 2/3rd has been applied to the prototype structure resulting in an interstorey height of 2 m and a building footprint of 4m x 3m (Ponzo et al., 2012). Many of the design details developed for stage one of testing have been used in the design of the experimental model (Fig. 2).

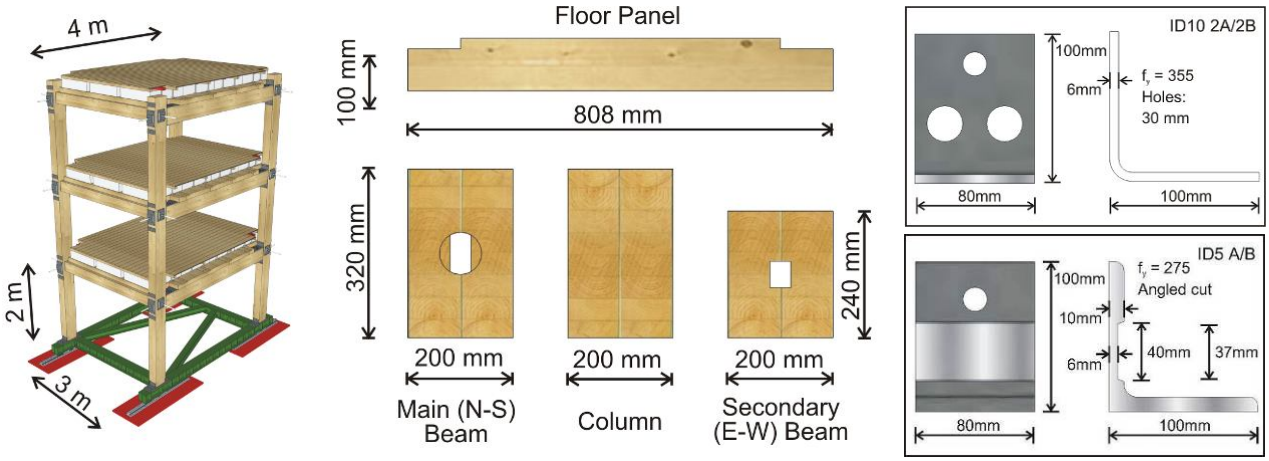


Figure 2: Test model overview and detailing and steel angle devices.

During testing passive energy dissipation devices will be added to the structure in order to add strength and reduce displacements without the increase of accelerations or base shears. 'Yielding steel angle' passive hysteretic energy dissipation devices are to be added to the frames and to the base of the columns (Di Cesare et al. 2013a).

The beam-column connection in the principle direction was based on the connection type which was tested during stage one (Fig. 3a). Passing through the centre of the beam is a single 26.5 mm diameter bar which is to be tensioned to varying values of initial loading throughout the test programme. This is a high strength steel bar with a yield strength f_{pyk} = 950 N/mm^2 and a Young's modulus of 170 kN/mm^2. Screws are used to protect the column face and long screws are used to fix each dissipater attachment plate. The various dissipater types are attached to the column though the use of M16 bolts which pass through the width of the column and attach to a backing plate. The column-foundation connection (Fig. 3b) is fitted with a steel shoe which is epoxied into the base of the column and left free to rock on a base plate which will be used to represent the foundations in the case of the test building.

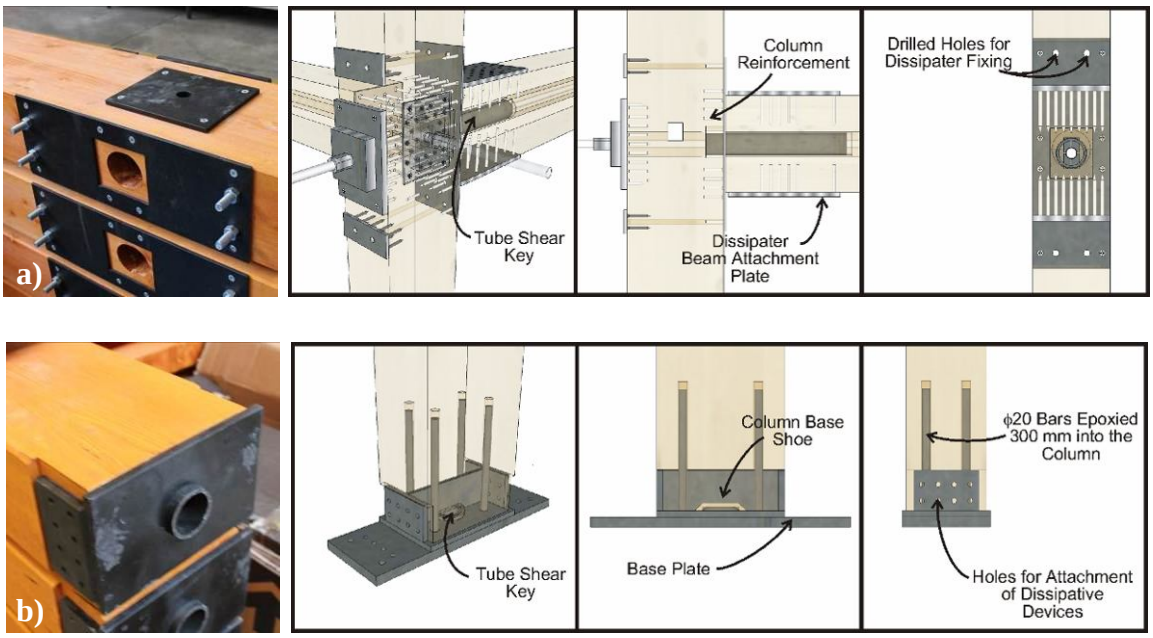


Figure 3: Post-tensioned Connections a) Beam to column and b) Column-Foundation.

The flooring spans in the secondary direction, therefore secondary beams are only required to provide torsional stability. In order to calculate the required amount of mass to be added to the test frame the masses of the prototype building must be scaled by the factor of 2/3rd observing mass similitude, related to the Cauchy-Froude similitude laws. This means that additional mass must be added which will also represents the presence of a factored live load. The additional mass required is made up of a combination of concrete blocks and steel hold downs with 12 blocks being spread out across each floor. For more information regarding the specimen design and construction refer to Ponzo et al. 2012.

During the testing programme several characteristics of the post-tensioned timber concept will be investigated with four main cases being selected. These options are based around the standard case of PT100_1.0 (Initial post-tensioning in the principle direction = 100kN and β = 1), adding steel angles without reducing the post-tension moment contribution gives case PT100_0.70 (initial post-tensioning = 100kN and β = 0.7). Adding steel in combination with a decrease in post-tensioning force, case PT50_0.80 (initial post-tensioning = 50kN and β = 0.8) decreases demand but retains moment capacity equal to that of case PT100_1.0. This configuration will also be tested without dissipative devices (PT50_1.0).

Seismic loading during testing will be mono-directional applied along the north-south axis of the building (Fig. 5). The full testing input will be a set of 7 spectrum compatible earthquakes selected from the European strong-motion database (ESD 2008) and 2 NZ seismic inputs from the recent Canterbury seismic sequence. The characteristics of the 7 European spectra are compatible with the code spectrum to which they were compared when considering their suitability. The code spectrum was defined in accordance with the current Eurocode for seismic design (EC8 2004) considering a

PGA for the design spectrum of 0.4375g and medium soil (soil type B). For preliminary dynamic identification, accelerogram 00196x has been considered (Fig. 4).

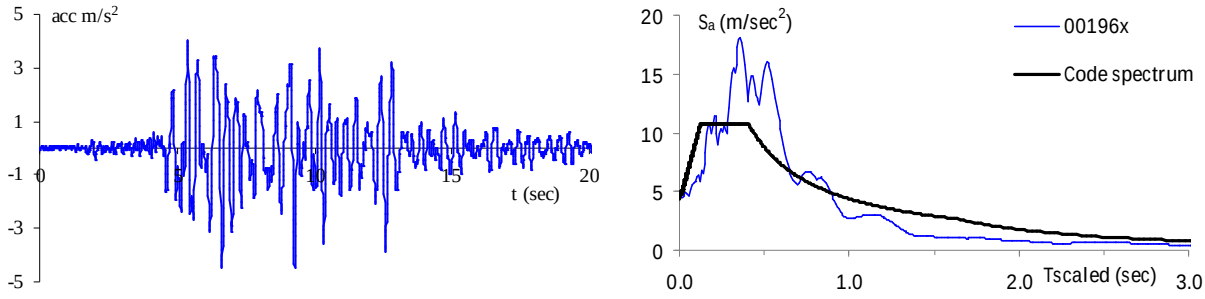


Figure 4: Accelerogram 00196x and comparison with considered elastic Code Spectrum

The experimental model (Fig. 5) was constructed in the brief time of two days by only four workers. In Figure 5 some images during construction and of the completed experimental model are displayed.

Figure 5: Multi-storey building constructed in UNIBAS lab

3. NUMERICAL MODELLING

From the conception of the post-tensioned jointed ductile connection it has been clear that the nature of the controlled rocking mechanism lent itself well to the use of a lumped plasticity approach in modelling (Palermo et al. 2005). This approach combines the use of elastic elements with springs which represent plastic rotations in the system. This method of modelling has been used in the predictive modelling of the structural behavior under the planned input loading. The specimen (Fig. 6) was modelled considering a series of rotational springs used to predict the moment rotation response of the post-tensioned beam-column joints and the effects of the presence of steel dissipation devices (Di Cesare et al., 2013b).

Recent studies have also recognized the importance of modelling and accounting for the elastic joint rotation in the calculation of rocking connection rotation therefore a rotational spring was added in the joint panel region. Rotational springs have been calibrated against the design procedure for the moment calculation of a hybrid joint presented in Appendix B of the New Zealand Code for the Design of Concrete Structures (NZS 3101:1995 2006). This procedure can be applied to the design of a timber hybrid connection provided a few simple considerations are made. The boundary conditions at the base of the model were also altered as (Figure 6). As the base of the column was left to rock the performance of this connection is complex (with moment capacity relying on a constantly changing axial load). During modelling therefore, this was varied from simple pin based or fixed base assumptions to the use of rotational springs and multi-spring elements.

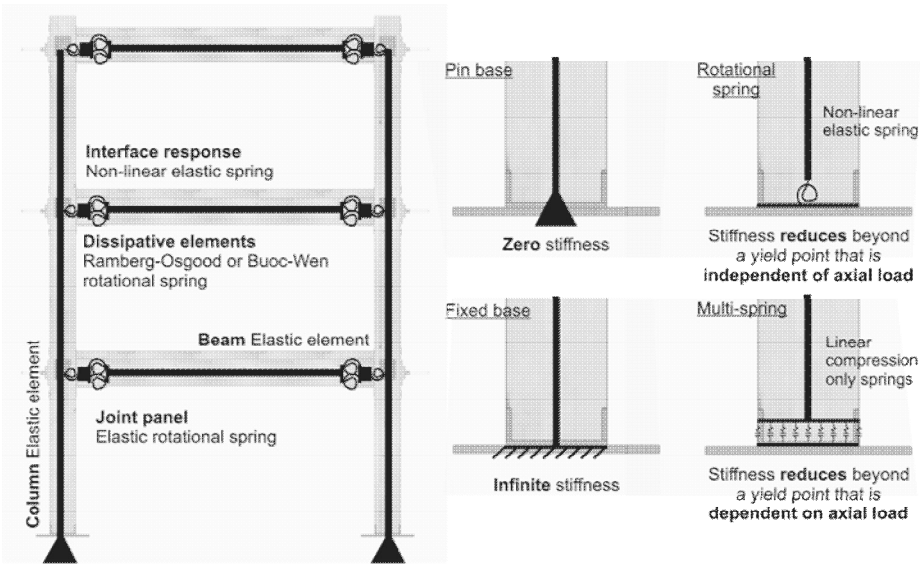


Figure 2: SAP2000 frame non linear numerical model

4. PRELIMINARY RESULTS

Preliminary testing on the frame without energy dissipation along with dynamic identification has been completed and the accuracy and adequacy of the numerical models when compared to these preliminary results is discussed in this section.

4.1. Shaking table tests

The experimental outcomes of the preliminary dynamic testing are compared with the 2-D numerical predictions considering the displacements at the second floor for accelerogram 00196x with an intensity level of 25%, of its maximum peak ground acceleration, with a damping ratio ζ of 3% for the fixed (Fig.7a), pin (Fig. 7b) and multi-spring base model (Fig. 7c) and 5% for multi-spring base model (Fig. 7d). As shown in Fig. 7c, the numerical multi-spring base model with 3% damping ratio provides a sufficiently accurate representation of the experimental performance.

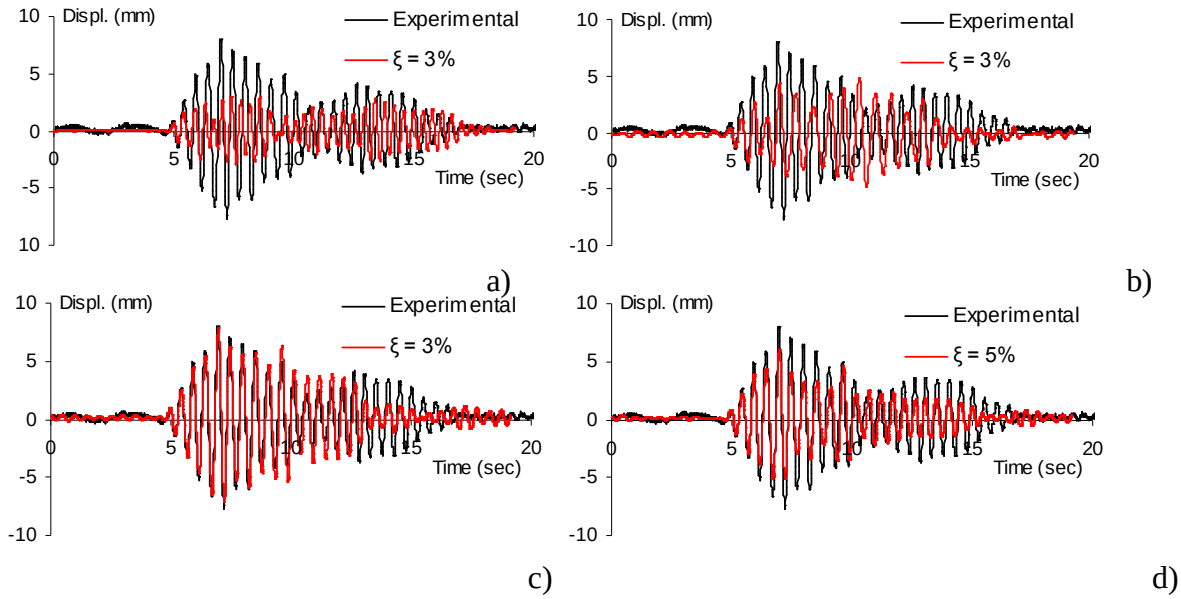


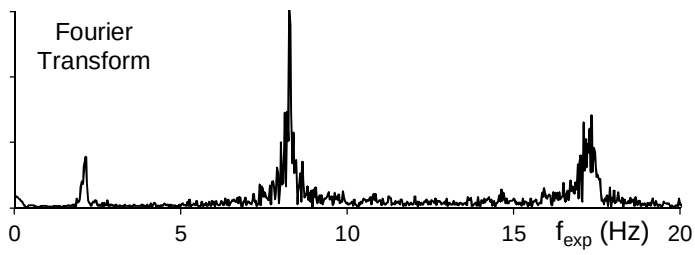
Figure 5. Comparison between dynamic test and numerical results for 00196 (intensity 25%).

4.2. Dynamic identification

Dynamic identification testing of the model was carried out in order to find its first three natural frequencies of vibration and considered a number of different excitation sources: hammer impact excitations and sine-sweep ground motion. In Table 1 dynamic characteristics are reported in terms of the experimental natural frequencies $f_{i,exp}$ corresponding to translational modes along the testing direction. As shown in Table 1 the numerical blind prediction ($f_{i,num}$) matches experimental results for the multi-spring base model. In order to obtain robust outcomes, in the table the average values measured at the upper level obtained by different excitation tests are reported.

Table 1: Comparison between dynamic experimental behavior and blind SAP prediction

Direction	Mode	$f_{i,exp}$ (Hz)	$f_{i,num}$ (Hz)
Transl. X	1	2.1	1.9
Transl. X	2	8.2	8.2
Transl. X	3	17.1	19.7



5. CONCLUSIONS

An extensive dynamic experimental testing programme on a multi-storey timber frame building is scheduled to be performed in the structural laboratory of the University of Basilicata in Potenza, Italy. The aim of the project, in collaboration with the University of Canterbury in Christchurch, New Zealand is to develop the innovative post-tensioned timber concept (under the name Pres-Lam) by extending its application to glulam timber and steel angle devices (Pres-Dis-Lam). Mono-directional shaking table testing will be performed on a 3-storey single bay frame scaled to 2/3rd. In this paper the design and detailing of the 2/3rd scale post-tensioned framed has been presented along with the details of the testing set-up. Initial comparison of displacements and natural periods shows good agreement between numerical predictions and test results for the more complicated base multi-spring model.

6. ACKNOWLEDGMENTS

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